Adv. Space Res. Vol. 15, No. 3, pp. (3)423–(3)426, 1995
1994 COSPAR
Printed in Great Britain.
0273–1177/95 $7.00 + 0.00

COSMIC DUST ANALOG SIMULATION IN A MICROGRAVITY ENVIRONMENT: THE STARDUST PROGRAM

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ABSTRACT

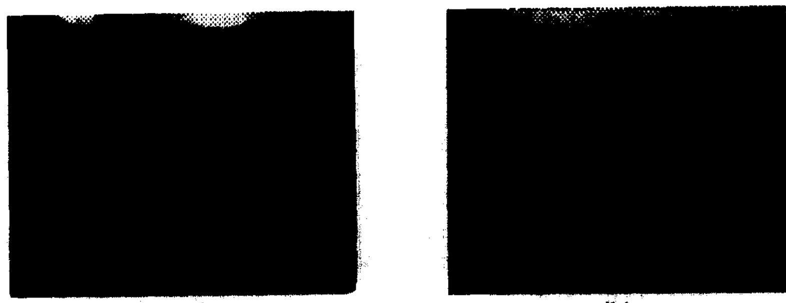
We have undertaken a project called STARDUST which is a collaboration with Italian and American investigators. The goals of this program are to study the condensation and coagulation of refractory materials from the vapor and to study the properties of the resulting grains as analogs to cosmic dust particles. To reduce thermal convective currents and to develop valuable experience in designing an experiment for the Gas-Grain Simulation Facility aboard Space Station, Freedom we have built and flown a new chamber to study these processes under periods of microgravity available on NASA's KC-135 Research Aircraft. Preliminary results from flights with magnesium and zinc are discussed.

INTRODUCTION

Small cosmic dust particles play an important role in several stages of stellar evolution. Major components of these interstellar grains are refractories such as silicates and carbides which condense in the outflows of red-giant stars. These refractory materials play a crucial role in the chemistry of the interstellar medium by serving as sites for chemical reactions and as regulators of the temperature in denser clouds by absorbing and re-emitting light. Furthermore, the condensation and later coagulation of such grains will lead to insights into the formation of larger bodies such as planetesimals and planets.

To understand how refractory particles form and grow we have undertaken a project called STARDUST as a collaboration between Italian and American investigators. The goals of this program are to study the processes of condensation and coagulation of refractory materials from the vapor and to study the size, morphology, mechanical strength, and optical properties of the resulting grains as analogs to the more complex cosmic dust particles. An important first step in this project is the production of a quiescent suspension of monodisperse, refractory particles. There is evidence that particles formed by nucleation and condensation of vapor are uniform in size with only a few, if any, aggregate clumps at the onset of formation. Although the nucleation of a few refractory systems has been investigated in terrestrial laboratories, accurate studies of the interaction between the fine-grained particulates are greatly hampered by particle settling effects. Resuspension of small particles by a burst of gas or by other mechanical motion will result in fast-moving, shearing flows and the break-up of some particles, while other aggregates formed during the settling process may never break up. Thus uniform, quiescent suspensions of monodisperse particles in a low pressure gas are difficult, if not impossible to achieve by the injection or resuspension of previously characterized particulates. Yet such well-characterized suspensions are ideal starting points for many of the more interesting particle interaction experiments envisioned for the Gas-Grain Simulation Facility on Space Station Freedom. It should be possible, however, to produce such suspensions by the direct condensation of refractory vapors under controlled conditions in a microgravity environment. The studies necessary to predict both the size distribution and characteristics of the particles produced by such a method may also yield high quality data on the vapor phase nucleation of refractory materials.

Previous experiments on condensation of refractory material from the vapor have also been affected by thermal convective currents arising from the high temperatures needed to produce such vapors. As a result we have designed and built a new apparatus which can be operated aboard NASA's KC-135 Research Aircraft. This aircraft flies in a series of parabolic arches and may produce approximately 23 seconds of weightlessness per parabola, thereby reducing thermal convective currents. This microgravity environment is not expected to affect the condensation process itself; rather it should provide a quiescent environment for condensation and coagulation which is easier to model and more suitable for producing uniform suspensions of condensed particles. These experiments also provide valuable information on the production of such refractory suspensions under sustained microgravity and are in fact crucial steps in the development of coagulation experiments for the Gas-Grain Simulation Facility for the investigation of the coagulation,



(a) (b)

Fig. 2. Digitized video images from experimental runs with magnesium at (a) 1-g and (b) microgravity.

RESULTS

To date, we have conducted experiments with only two metals: magnesium and zinc. These two materials are not especially important in astrophysical environments, although magnesium is one of the more abundant metals in such systems. We have chosen these elements for our initial experimental studies because of their relatively high vapor pressures. As we develop our apparatus we will study more refractory, and therefore more relevant substances such as iron metal and magnesium and iron silicates. We have tried to apply Hale's Scaled Nucleation theory to the experimental results for both magnesium and zinc, but the data and the theory do not agree. According to Hale's theory, a plot of $(\mathrm{LnS})^{2/3}$ vs. $(1/T)$ should yield a straight line and the ratio of the slope of this line to the negative of the intercept should yield the critical temperature of the material. Thus far, application of the scaled theory to the magnesium and zinc data have yielded unreasonably low critical temperatures. Just recently, we have re-examined shock tube data for iron, bismuth and lead in the form suggested by Hale and found similarly low critical temperatures, at times even below the boiling point[4]. Therefore we are currently re-examining the apparatus, the models of the data, and the theory to understand this discrepancy.

The immediate major goal of our work is the production of uniform suspensions of refractory particles. Although we do not yet have a quantitative way of rating the uniformity of the cloud of smoke particles, by eye the clouds obtained in zero-g appear to be quite uniform. Figure 2 shows a comparison between the smoke clouds formed under terrestrial and zero-g conditions. Each figure is a digitized video image of the viewing region of the chamber taken during experimental runs with magnesium. The source of vapor is a spout which appears as a bright spot at the top-center of each image. The figure under 1g shows a cloud which is nonuniform and exhibits convective swirls. The image obtained in zero-g shows what appears to be a uniform suspension of particles. Surrounding the vapor spout there is a region which is free of particles. During an experimental run in zero-g the smoke cloud slowly moves away from the vapor source, but this particle-free zone remains essentially stationary. In our nucleation experiments we are trying to measure the temperature and vapor concentration at the interface between this particle-free and particle-rich region.

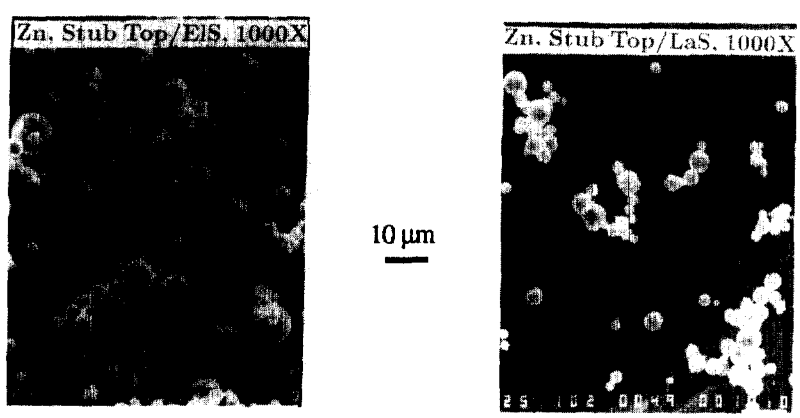


Fig. 3. SEM micrographs of zinc particles at 1000X magnification. Note aggregates which look like the initial stages of growth of fractal-like particles.

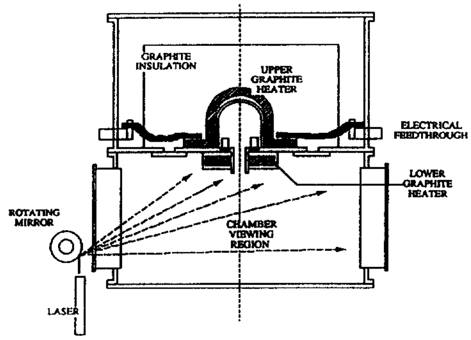


Fig. 1. Experimental chamber used on NASA's KC-135 aircraft.

mechanical strength, and optical properties of aggregates of refractory particles. It is believed that during extended periods of weightlessness suspended particles could coalesce into very different structures than are formed in a 1g gravitational field--perhaps producing "fluffy" or "fractal-like" structures. These resulting open and porous structures could have very unusual optical and mechanical properties. It is impossible to form such aggregates on the ground since any force applied to arrest their settling is likely to crush these undoubtedly fragile structures. The periods of weightlessness on the KC-135 are unfortunately too short to study more than just the initial stages of coagulation, yet these flights will provide excellent experience in producing uniform, quiescent suspensions and developing *in situ* techniques for characterizing the particles and monitoring their interactions.

PREVIOUS WORK

In addition to providing valuable experience in the production of suspensions of refractory particles from the vapor, experiments on condensation in a microgravity environment may also provide useful information on the nucleation of these materials. Most of the experiments in refractory nucleation have been performed with two types of apparatus--the shock tube technique and the gas evaporation method. The results of both types of experiments are the same: none of the experimental data agree with Classical Nucleation Theory or its modifications such as the Lothe-Pound formulation. To date, only Hale's Scaled Nucleation theory has compared successfully with any experimental nucleation data, and only for two gas evaporation studies of silver and SiO[2]. Hale's theory predicts a relationship between the critical supersaturation, S_c, and the condensation temperature, T, as follows:

$$\ln(S_c) \approx \Gamma\Omega^{3/2}\left[\frac{T_c}{T} - 1\right]^{3/2} \qquad (1)$$

for a flux of particles of $1/cm^3$-s[3]. In this expression the quantities Γ and Ω are essentially constant and T_c is the critical temperature of the material. Equation (1) works quite well with many volatile substances such as water and alcohols, and for the experimental data for silver and SiO. Only a handful of refractory compounds have been studied and more experimental data on additional refractory substances are needed to test the validity of this or other theories.

EXPERIMENTAL APPARATUS

To study the condensation of refractory vapors and the coagulation of the resulting grains we have designed and built the chamber shown in Figure 1. It consists of a cylindrical vacuum chamber separated into two sections. The upper section contains the material to be studied within an alumina crucible and surrounded by a set of graphite resistive heaters and insulation. The lower half of the chamber is the viewing region of the apparatus. The graphite heaters serve two purposes: they produce the refractory vapor and establish a temperature gradient in the viewing region. A laser beam strikes a rotating, multifaceted mirror and produces a two-dimensional fan of illumination within the chamber. When vapors from the heater assembly diffuse into the viewing region, the fan of laser light illuminates only a cross-section of the condensed smoke particles. The pressure, acceleration level and temperatures throughout the chamber are recorded using a computerized data acquisition system.

We have not quantitatively measured the size distribution of the smoke particles within the cloud during individual parabolas. We have collected particles on SEM grids from various locations with the chamber. Figure 3 is a set of SEM micrographs from an experiment with zinc metal. The particles in these micrographs appear to be spherical and rather uniform--both of which are desirable in the design of a coagulation experiment. In some cases there are aggregates of these small particles which are branched and chain-like. These particles may be the initial stages of some of the fractal-like particles we are interested in growing. Some of the nonuniformity of the particles could be due to the changing conditions and different times in which they adhered to the SEM grid. During a typical flight, we undergo approximately 40 parabolic arches; we do not yet have a method of collecting particles from an individual parabola or from specific regions of the smoke cloud. We are in the process of designing a more sophisticated particle collection facility to eliminate this problem.

FUTURE WORK

Refractory species over a range of volatilities will be investigated to study the basic mechanism of the nucleation and condensation phenomenon. Thus far we have studied magnesium and zinc, species with relatively high vapor pressures. Examples of intermediate volatility species are SiO and iron and these materials are being planned for later experiments. Eventually we also want to study "super refractory" species such as carbon, silicon carbide and aluminum oxide. These compounds cannot be vaporized from standard crucibles and will require significant modifications to the existing apparatus. Not only will higher vapor source temperatures be required but the method of producing vapor will have to be redesigned as well.

A sampling system for extracting particles from the chamber during the experiment, and the capability for *in situ* particle characterization will also need to be developed. These would help to differentiate between the design change effects and those caused by the extended exposure of the condensate particles to the varying environmental conditions in the chamber through the series of parabolic maneuvers.

CONCLUSIONS

We have presented an overview of the STARDUST program, a program with long-term goals which include studying the condensation, coagulation, and physical and optical properties of refractory particles as analogs to cosmic dust grains. We have made good progress towards these goals by producing uniform suspensions of particles from the vapor. The next step is to develop a more sophisticated method of characterizing the resulting particles and improving the data collection and analysis of the nucleation of these particles.

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